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Experimental and Theoretical Studies of Three-Phase Relative Permeability

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Abstract

The three-phase relative permeability relations define the hydrodynamics of fluid flow in porous medium. These relations are necessary for simulation of various phenomena occurring in the reservoir during various production and enhanced oil recovery (EOR) processes; such as chemical flooding, steam flooding, enhanced gas drives, etc.

Despite the availability of a modest number of relative permeability measurements reported in literature since 1941, there is no universally accepted conclusion reached on the shape of the isoperms. Given this scarcity of consistent experimental data, it is difficult to recommend any of the developed predictive models, e.g. empirical, mechanistic, or pore-level, for the estimation of isoperms of each phase under reservoir conditions. This paper presents a review of a wide rage of experimental results reported on three-phase relative permeability and highlights their salient features and distinctive findings. It also provides in-depth evaluation of technical achievements in this field. The present study is a useful reference for engineers and scientists interested in modeling of multi-phase flow in porous media, and provides guidelines on the selection of predictive models for generation of three-phase relative permeability isoperms.

Introduction

The three-phase relative permeability relations define the hydrodynamics of fluid flow in porous medium. These relations are necessary for modeling of multiphase flow in porous media, such as chemical flooding, steam flooding, and enhanced gas drive systems. Despite the availability of modest number of relative permeability measurements in literature since 1941, reported by Leverett and Lewis, there are a few sets of three-phase relative permeability measurements in literature which are limited to specific porous medium. Because of the scarcity of reliable experimental data and complexities of three-phase relative permeability measurements, the most common engineering practice for estimation of isoperms of various phases is using theoretical models. These models usually use information, such as two-phase relative permeabilities, capillary pressure, and/or saturation history to predict three-phase relative permeability isoperms.

This paper presents a comprehensive review on three-phase relative permeability measurements data available in literature. Through this paper, first reported experimental studies in literature are screened to highlight various relative permeability measurement techniques and effect of various parameters, e.g. interfacial tension and temperature, on three-phase flow behavior. Next, the main three-phase relative permeability models in oil and gas industry are presented. Finally, the comparative study of 13 different three-phase relative permeability models for six different experimental data sets (i.e. Corey *et al.*, 1956; Donaldson and Dean, 1966; Saraf *et al.*, 1982; Maini *et al.*, 1990; Oak, 1990 and 1991) are presented. This study shows among selected models, no single model is capable of predicting oil isoperms in all data sets satisfatorily. Therefore, this paper clearly highlights the necessity for examining predictive models against experimental data prior to using them for modeling purposes, as well as the need for better and more comprehensive models for prediction of three-phase relative permeability. However, one should bear in mind that part of this discrepancy in the models' predictions can be attributed to the sources of the data used in evaluation studies. These data sets may not be uniform in the direction of saturation change or not complete in that they do not include both two- and three-phase relative permeability measurements as well as capillary-saturation measurements.

Review of Three-Phase Experimental Studies

Experimental measurements of three-phase relative permeability were reported as early as 1941 by Leverett and Lewis and have continued to trickle into the literature. Levrett and Lewis conducted steady-state three-phase relative permeability measurements in a tightly packed sand core. In these experiments, brine (sodium chloride), nitrogen, and kerosene (1.67 mPa.s) and kerosene-motor oil (18.2 mPa.s) were used to determine the three-phase relative permeability and effect of